Nanosat Intelligent Power System Development

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Abstract

NASA Goddard Space Flight Center is developing a class of satellites called nano-satellites (Nanosats). The technologies developed for these satellites will enable a class of constellation missions for the NASA Space Science Sun-Earth Connections theme and will be of great benefit to other NASA enterprises.

A major challenge for these missions is meeting significant scientific objectives with limited onboard and ground-based resources. Total spacecraft power is limited by the small satellite size. Additionally, it is highly desirable to minimize operational costs by limiting the ground support required to manage the constellation.

This paper will describe how these challenges are met in the design of the nanosat power system. We will address the factors considered and tradeoffs made in deriving the nanosat power system architecture. We will discuss how incorporating onboard fault detection and correction capability yields a robust spacecraft power bus without the mass and volume penalties incurred from redundant systems and describe how power system efficiency is maximized throughout the mission duration.

1. Nanosat Overview

The primary objective of the GSFC Nanosat development effort is to enable flying tens to hundreds of nano-satellites in a constellation to make multiple remote and in-situ measurements in space [1]. This will revolutionize the scientific investigations of key physical processes explored by the Space Science and Earth Science communities. To enable this goal, we must develop advanced technology that is low cost, lightweight, low power and survivable in a space radiation environment over a two year mission lifetime.

The next generation of Space Science missions requires the deployment of multiple spatially separated sensors to answer fundamental questions that arise in NASA's Sun-Earth Connections (SEC) theme [2]. Magneto-spheric Constellation (MAGCON), a keystone mission on the SEC Roadmap, is to obtain the first dynamic overview of Space Weather. To implement MAGCON numerous weather stations (tens to hundreds of spacecraft) must be placed in orbit about the Sun and the Earth. Thus this constellation of spacecraft must be simple and economical to build, orbit, and operate. The spacecraft must withstand demanding physical conditions and long communication blackouts, while meeting demanding data return requirements. As Earth, Planetary, and Deep Space missions share similar concerns, the enabling technologies we are developing apply. These demands are driving spacecraft technology toward smaller, constrained spacecraft: Nanosats.

Nanosats will be small, efficient, and capable spacecraft that enable missions requiring multiple independent instrument platforms. Smaller, however, does not necessarily mean less capable, but it does require a highly integrated system with intelligent control strategies. Resources to support redundancy are not available. In this paper, we focus on the Electronic Power System (EPS) of the Spacecraft. We will discuss how integrating the power system with other subsystems enables more capable spacecraft. In addition, we will discuss how the EPS architecture and advanced autonomous control strategies eliminate string redundancy and enhance spacecraft reliability and reduce ground support costs.

To enhance reliability and eliminate string redundancy, we turn to robust, autonomously adaptive systems. Care is being taken to implement solely within the local power subsystem only those tasks absolutely necessary for immediate health and safety. Other tasks that may be required only periodically will be implemented remotely on the spacecraft CPU. The spacecraft will operate as a ‘single string' system since redundant hardware or software is not implemented.

1.1 Spacecraft Redundancy

Nanosats are not large enough to support the traditional concept of component redundancy to implement fault tolerance. Indeed, Nanosats are so restrictive that many spacecraft systems must be developed in an integrated way to symbiotically satisfy multiple needs, e.g. structural, thermal, and power. Individual components provide multiple functionality, so Nanosat operates as a single-string system, where the failure of one function may stop the system. Fault tolerance and availability of operation are obtained with Nanosat through multiple spacecraft, but as in the game of chess, one should not waste one’s pieces. The spacecraft must be made as robust as possible, and care must be taken to ensure that systematic problems do not arise among the elements of nanosat constellations. In this way, though individual Nanosats may degrade and fail, the capability of the Nanosat Constellation will more gracefully decay.

2. Challenges and Constraints

The MAGCON mission samples a large fraction of the Earth’s magnetosphere. Many MAGCON Nanosats will have orbital periods of ten or more days. With their low power and small antennae, Nanosats will only be able to communicate with the ground for the few hours when the spacecraft is near perigee. The ten day communication blackouts lend an extreme Deep Space character to Space Science Nanosat missions. To put this aspect of Nanosat requirements in perspective, the round trip light travel time between Earth and Pluto is between 8 and 14 hours. The operators of a mission to Pluto would likely learn of and respond to problems with their spacecraft more rapidly than would operators of MAGCON Nanosats. To be fair, these Nanosats will have much better communication rates to ground at perigee than a spacecraft at Pluto. But MAGCON Nanosats will have to take more responsibility for their own function than previous solar terrestrial probes [3].

3. Traditional Power System Control

Traditional spacecraft design has focused on providing redundant equipment and configurations in order to provide effective mission support in spite of equipment failures and system degradation. In order to utilize these capabilities, a large number of telemetry points, or system data parameters, are provided to assist ground controllers, and in some instances, flight processors, in determining when and if failures occur. It should be noted that ground control plays a major role in this process. Except for a limited number of exceptions, system monitoring, anomaly detection and workarounds are performed by ground control. That is, all these functions are manual in nature. Although more autonomous operating procedures are being implemented for some newer, larger spacecraft, in the large majority of cases, if people don’t see or do it, no action will be taken.

Two distinct groups of people make up the staff of a ground control center. Flight operations personnel are the people who routinely monitor the spacecraft during the periodic communications periods, called "passes". Depending on the kind of support being received, passes can be as short as ten to fifteen minutes in duration. During this time, real-time data must be analyzed, recorded playback data recovered, computer memory loaded, and spacecraft systems monitored for anomalies. Obviously, this leaves little time for any workaround activity other than the most fundamental, predefined anomaly reaction procedures.

This is where the engineering staff participates in the effort. If anomalies occur during off hours (most seem to) the flight operations team contacts the engineer on duty. During working hours they may be in the control center itself. Real time and playback telemetry is reviewed, the anomaly identified and reaction plans developed. This can take hours or even days for severe problems. Most systems have "safe modes" that can be automatically triggered if severe problems occur, but these typically only put the spacecraft into safe configurations. They do nothing to address the anomaly, but almost always seriously affect mission effectiveness. Also, some safe modes require a great deal of effort to recover from.

Finally a reaction plan is developed and command sequences prepared. They are then executed when communications with the spacecraft are next established. Simple sequences can be done in one pass, more complex procedures can take extended periods of time. A spacecraft with a large amount of redundant hardware and a complex set of possible configurations provides a range of responses, but also increases the amount of time necessary to prepare anomaly responses. It should be obvious that the traditional method of spacecraft control can be demanding and time consuming.

Furthermore, controlling a nanosat constellation is, on the face of it, more difficult than controlling one The spacecraft assessment and command generation for one-hundred individual idiosyncratic spacecraft is an incredibly challenging task.

4. Why autonomy?

The Electrical Power System (EPS) requires a degree of autonomy for solar array regulation, selection of battery charge rates, bus voltage regulation, load predictions, power availability, load shedding, circuit protection, optimization of the power system and reliability management of EPS cognizant areas.

Constellation missions involving as many as a hundred spacecraft are a primary application of Nanosats. With so many Nanosats in a mission, it would be difficult to handle these by collecting the data, coding it, sending it to the ground, interpreting it, getting a human to look at it, make a decision, code the command, send it to the spacecraft, and insure the command was executed. This typical chain of events also requires more resources for Command and Data Handling (C&DH) and Communications (COM) functions, and thus more power from the EPS. There is a great benefit for the EPS and for the rest of the spacecraft for as great a degree of autonomy as possible on the Nanosats.

Ordinarily this degree of autonomy would require more processing power, however many EPS autonomy functions will be implemented locally independent of the Nanosat CPU.

4.1 Single-string Reliability through Component Adaptability

Having multiple spacecraft in similar orbits provides a basic measure of fault tolerance and availability, but spacecraft redundancy does not ensure spacecraft effectiveness. In fact, this sort of redundancy carries its own risks: two eggs dropped on the floor break about as quickly as one and leave behind a bigger mess.

The spacecraft must be made as robust as possible, and care must be taken to ensure that systematic problems do not arise among the elements of Nanosat Constellations.

To enhance reliability while eliminating string redundancy, we turn to robust, autonomously adaptive systems. Only those tasks absolutely necessary for short term (instantaneous) functionality are implemented within the local EPS. Less frequently executed tasks will share the spacecraft CPU with other spacecraft functions. The spacecraft, particularly the hardware component, will operate as a 'single string' system.

An example is the NASA Earth Science Mission EOS-AM battery design where two batteries are provided: either single battery would not be able to provide the mission requirement. Cell redundancy is incorporated into the design with cell by-pass circuitry to eliminate any cell that goes open-circuit. The bi-directional charger/discharger called the BPC will automatically sense the reduction of a cell and compensate for the battery operation. Thus, instead of having redundant strings, we place redundant elements within a string. EOS-PM and MAP (Microwave Anisotropy Probe) battery designs rely even more on cell redundancy, the second battery is eliminated, leaving these systems with a single battery.

A similar opportunity exists with solar arrays. The Nanosat solar array concept, like most solar arrays is made up of many solar cells in a series string, with many strings in parallel making up the system voltage and power requirement. The proportion of the load that any one solar string is supplying power to can be adjusted to provide system performance with redundancy. When the performance of a string degrades, the electronics will adjust the voltage output so the string still contributes power, though at a lower level. Thus, Nanosat operates as a single-string system, where the failures are tolerated by system self-adjustment.

4.2 Component Adaptability and Multi-use

We see that within the EPS there are opportunities for redundancy. Clever use of interdependence and parallelism enables adaptability as mentioned above. It also enables economical applications of resources. For example we are exploring a structural battery that will incorporate a mounting surface for the solar cells and will also serve as a spacecraft support structure. We are even exploring embedding our power electronics within the structure. In a sense, we are adapting power system components to meet EPS and spacecraft needs in novel ways. This integrated approach requires coordination among spacecraft disciplines, but Nanosat demands the reduction in overhead resource costs.

5. Intelligence and Autonomy

In the context of robust and adaptive subsystem infrastructures, a symbiotic relationship between hardware-based and software-based logic could make possible the realization of the high level of autonomy desired for Nanosat in spite of its limited processing resources. One promising model of Nanosat autonomy is that realized by such a shared responsibility between hardware and related software in Nanosat's shared processor.

For a primary spacecraft function, the hardware-based autonomy will readily support the handling of situations that require a quick simple reaction. However, those situations which require more deliberation before acting will be handled by the autonomy-related software stored in the shared processor (Figure 1).

5.1 Activities

There are three basic types of activities that will be supported by the autonomy-related software in the Nanosat shared processor. These are: Trending, Science management, and FDIR (Fault Detection, Isolation, and Repair).

Trending activities deal with predictions. From continuous spacecraft function or instrument state information, a trending function could be exercised to establish the possibility of eventually entering an anomalous state. The system could then initiate corrective actions to avoid the anomalous situation.

Science management activities are focused on the use of heuristics to assign degrees of interest to the science data available and only store high-interest data.

FDIR activities come into play when an anomalous situation occurs in either a spacecraft function or experiment package. State information is used to determine that an anomaly exists. The FDIR logic then isolates the fault, i.e. determines the fault's location, and initiates a sequence of (usually) pre-stored actions to get the spacecraft function or experiment package back to a good state.

5.2 Technologies

There are several overlapping autonomy-related technologies that can support these activities. These are:

- Rule-based: quick reaction;
- Model-based: deliberative reasoning, planning for action;
- Neural nets: classification of faults;
- Fuzzy Logic: approximate reasoning that deals with inexact data;
- Heuristics: rule-of-thumb reasoning.

The autonomy resource on Nanosat can make use of the appropriate technology based on the situation and the nature of the data and information that needs to be reasoned with.

5.3 Current Applications

The realization of ground-based and space-based autonomy already has a strong and vibrant history. Here are a few examples [4].

The ground systems for such NASA/GSFC missions as GRO, XTE, MAP, IMAGE, TRACE, and HST all include elements of autonomy to assist human operators and analysts in the execution of their tasks.

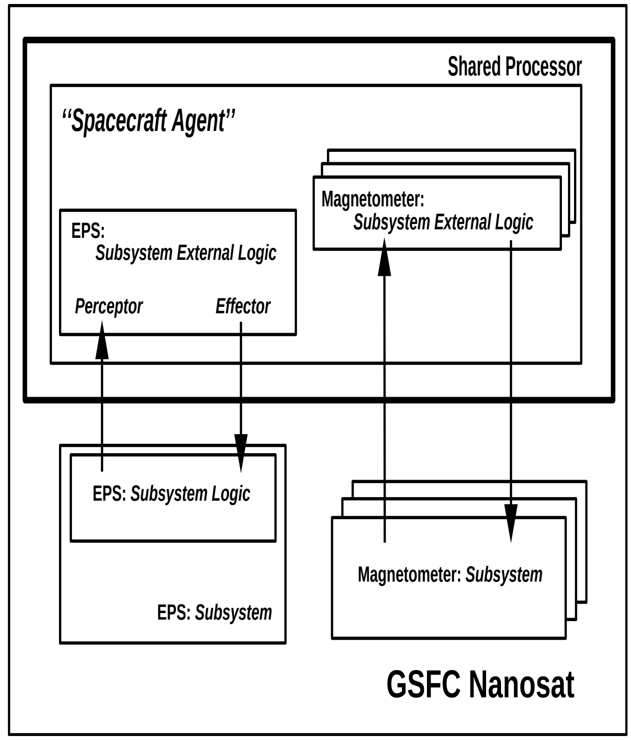


Figure 1. Nanosat EPS control concept.

Applications of technologies like expert systems, neural networks, fuzzy reasoning, and model-based reasoning are becoming commonplace.

The second phase of the experimental agent-based ground operations system LOGOS (Lights-Out Ground Operations System) is under development. It has already shown how a community of agents can successfully act as surrogate controllers in an autonomous ground system.

Space-based systems are also participating in the encroachment of autonomy on operations. Autonomous attitude control systems are a critical spacecraft technology in use today. Autonomous navigation and on-board maneuver planning are being realized. The application of fuzzy controller technology supports this focus. The Remote Agent project has resulted in an experimental use of agent technology on the Deep Space 1 (DS1) spacecraft. Extensive use of model-based reasoning for health and safety functions and spacecraft activity planning support this activity. The adaptive scheduler work for

Next Generation Space Telescope (NGST) will contribute to better science agenda management.

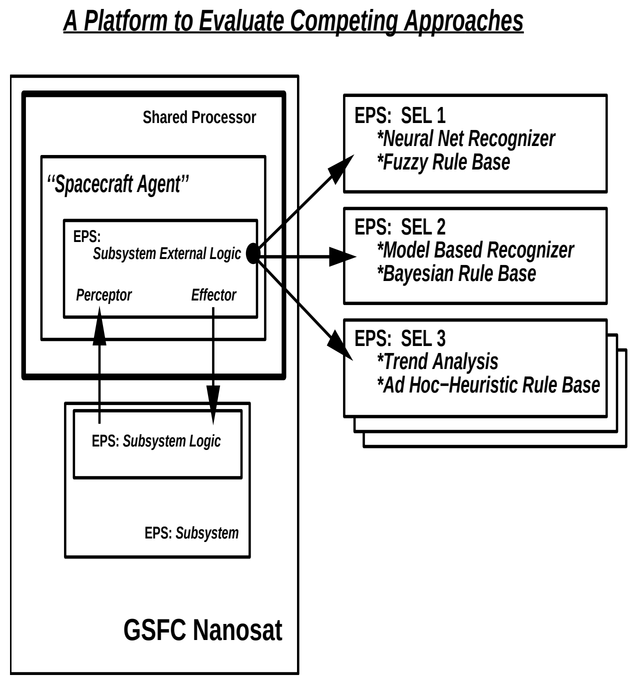
Nanosat is in a position to significantly profit from these autonomy successes. It will also contribute to optimizations of the autonomy-related technologies because of its resource constraints.

These techniques are critical to achieve the goals of some Nanosat applications. But what are the more immediate applications of the techniques of this section to Nanosat EPS?

5.4 Intelligence and EPS

In this section we discuss how onboard intelligence enhances the autonomy and function of the EPS. By intelligence we broadly mean the ability to learn or understand: it is the ability of the EPS to make decisions or change its behavior in light of its history. One strategy to obtain this adaptability is to make that history as uneventful as possible. In Section 4 we described an approach to achieving a large measure of autonomy through judicious design. There is not much to go wrong in an EPS designed for simplicity, nor is there much to configure or monitor. Thus the EPS is designed to provide simple behaviors and controls.

The simplest way to build independence of human control into the EPS is to design a predictably steady, no-maintenance, robust system that lasts long enough to get the job done. Many aspects of the health and safety of the EPS must be designed into the system, for example, the safe operation of spacecraft batteries. By using low- or no-maintenance battery technologies and circuit designs that avoid overcharging, the Nanosat EPS has fewer degrees of freedom that require control, and certain faults are avoided. Unlike traditional power systems, most degrees of freedom of the EPS are handled internally. Or put another way, the system is being designed with a few degrees of freedom as possible. A simple rule base running on a shared processor



`Figure 2.` The EPS is being designed so that different control schemes may be quantitatively compared and analyzed.

or an embedded EPS microcontroller could control the remaining degrees of freedom. Thus EPS would monitor its battery charge, prescribe a charging rate, and could be smart enough to compensate for battery or solar cell failures as described above. Nanosat EPS is being designed to evaluate competing technologies
to implement these control functions (Figure 3), Fuzzy Logic is one key technology we are evaluating.

5.5 EPS Operation

Much EPS intelligence and adaptability is designed into the system itself to maintain the health of EPS components. Therefore, we introduce the concept of a Spacecraft Agent (SA) that is responsible for those things the EPS and other subsystems cannot do for themselves. This concept is similar to the New Millenium Remote Agent (NMRA) architecture being tested on board DS1 [5]. The NMRA uses a variety of advanced AI techniques to achieve mission goals, and onboard planning and scheduling is major cost for the NMRA. The NMRA makes extensive use of Model-Based- Reasoning to determine and predict spacecraft state and to instruct the formation of plans of action [6]. We do not foresee the Nanosat SA requiring the same degree of complexity that DS1 requires, so we are focussing our efforts to design Nanosat with simplicity and autonomy as key features from the start. On the other hand, the rapid advance of computing capability may make approaches such as used in DS1 more applicable, therefore we are considering the costs and benefits of such software agent based autonomy.

The main point is that we can design spacecraft subsytems to be controlled by the SA. Nanosat development will create systems that operate with as little external input as is reasonable: simply reinstating the traditional command and control capability outlined in Section 3 on board the spacecraft is not our aim.

So if we have done our job in making a reasonably worry free EPS, what tasks are left over for the SA to handle? The key functionality that SA can add to EPS operation is the distribution of power to spacecraft components. Decisions about power distribution are to be deliberately left outside the purview of the EPS. The EPS provides electrical power and information about its current state, e.g. its current store of energy and its power production rate. The SA will have a planning and scheduling capability where it maps out its actions based on its understanding of the electrical sources, loads, and mission policy.

SA will contend with issues and conflicts that arise as it makes sure that Nanosat has enough power to meet mission critical objectives. The SA must ensure that there is enough power to keep memory alive through eclipses and that the spacecraft has the power to communicate with the ground at perigee. Science instruments and other functions, e.g. C&DH, COM, usually have a number of modes of operation that require different amounts of power; the SA will set the modes of operation based on mission policy. In general, EPS is designed to provide the maximum required power, in which case, SA power allocation becomes important when there is a spacecraft fault. However, we know that EPS's power output will degrade over the lifetime of the mission, therefore it makes sense to design the spacecraft to be able to adapt to the decline of this resource.

Hence, SA will allocate power, and, if possible, SA will optimize power use per mission policy, e.g., to maximize the amount of Science data returned to Earth. Making these and other run-time decisions is the main function of the SA; how these decisions are made depends on the complexity of mission policy and the available resources.

5.6 EPS Maintenance

As stated above, the EPS provides the SA with information that SA uses to make and act on decisions. Following trends, e.g. power balance over time, is one possibly useful long term activity for the SA. Temperatures, currents, voltages may also provide insight into how the EPS is functioning. But what can the SA do with this information? What control points does EPS provide to SA? If the EPS team is successful, the answers to these two questions are very little and very few. Battery reconditioning is a prime example of our approach. Charge cycling some types of batteries improves their performance, but criteria and decisions must be made about when and how to perform this reconditioning. The logic associated with these criteria, decisions, routines, plans, and schedules must exist onboard the spacecraft either within the EPS or the SA. As discussed in sections 2 and 3, open-loop command is not an option. By choosing a battery technology that does not require reconditioning, one reduces the costs of the overhead required to make the decision. However, EPS function has not necessarily been diminished by using an alternative battery technology, in fact system performance has just been enhanced.

A key goal of the GSFC Nanosat Team is to identify such opportunities for efficiency and aggressively take advantage of them. We believe that this approach will enable the application of a greater range of autonomy-related technologies onboard spacecraft. By judicious design, we will free the resources necessary to use more expensive techniques where they are truly required. However, this requires communication, coordination, and collaboration between mission and system designers, i.e. between and amongst scientists and engineers. Designs and requirements must iterate back and forth between these diverse groups of people, so that the group as a whole understands the implications of their decisions. This is likely the most difficult challenge. (Note that this is forced on us by the expense of putting things into space.)

5.7 Spacecraft Agent Implementation

How the SA is to be implemented has not yet been determined, because there is still considerable time before the first Nanosat mission. Subsection 5.2 above lists a number of technologies that could be used; each technology has its own advantages and disadvantages. The Nanosat EPS is being designed to make it easier to use a broader range of these technologies, so that we can use the tool that seems most applicable to the task at hand. Heuristics based in Fuzzy Logic are strong contenders for several aspects of the system because they are efficient, convenient, and have been successfully deployed in the past.

5.8 RISC and Spacecraft System Design

In a sense, our approach is analogous to that taken by the developers of RISC technology for microprocessors. Reduced Instruction Set Computers feature simplified memory access and other functional behaviors. The regularity and simplicity of instruction sets based on load-store processor architectures allow compilers to produce smaller, more efficient executables [7]. We are pursuing simpler, more regular functions to ease the task of the Spacecraft Agent (SA). A compiler makes decisions about how a processor is to behave, just as the SA makes decisions about how the spacecraft is to behave.

6. Conclusion

The GSFC Nanosat EPS is being designed to meet the requirements of the future Constellation missions by novel means. Since many of the challenges we face are common to all small, inexpensive spacecraft, our approach will benefit a range of applications. The EPS architecture enhances reliability and eliminates string redundancy. Low-bandwidth tasks are implemented at the local level. Other tasks will be implemented remotely, sharing resources of the spacecraft CPU, and communicating as required with the local power electronics. Several control strategies are being analyzed to facilitate the autonomous operations imposed by the ten day orbit. Control strategies that are currently resource intensive will be enabled through the judicious design of spacecraft subsystems. The desired behaviors of the Nanosat EPS are simple, and the subsystem’s internal degrees of freedom need not be many, therefore its control scheme can be simple and complete.

Finally, the PSE will be implemented as one of several components in a highly integrated spacecraft. This will facilitate optimizing the control strategy of all the spacecraft operations, thereby enhancing the reliability, robustness, and function of the spacecraft on orbit. All Nanosat functions, including EPS, C&DH, COM, etc., will also follow this strategy of behavior simplification, regularization, and closure.

7. References

[1] "NASA-GSFC Nano-Satellite Technology Development", P. Panetta et al, *12th AIAA/ USU Conference on Small Satellites,* 1998.

[2] Further information about the NASA's Sun-Earth Connection theme can be found at *http:// www.hq.nasa.gov/office/oss/sec*.

[3] Information about the ongoing International Solar Terrestrial Physics line of probes is

available at *http:// istp.gsfc.nasa.gov*. Spacecraft of the Solar-Terrestrial Probe Line are the next generation of platforms to explore the Sun-Earth Connection, see note [2] for details.

[4] More information about NASA/GSFC's autonomous systems development is available through the Information Systems Center: *http:// isc.gsfc.nasa.gov,* and *http:// agents.gsfc. nasa.gov*.

[5] An overview of the first AI system to control a spacecraft is given in B. Pell; et al., A hybrid procedural/deductive executive for autonomous spacecraft. *Autonomous Agents 98,* Minneapolis MN USA. 1998.

[6] Papers related to Model Based Reasoning as applied to Deep Space One can be found at: *http:// ic-www.arc.nasa.gov/ic/ projects/mba.*

[7] A splendid little discussion of RISC issues in the context of code-generation by compilers is: N. Wirth, 1986, *Communications of the ACM*, Vol. 29, No. 10, pp 978-990.

8. Biographies

Michael A. Johnson is a senior electrical engineer in the GSFC Microelectronics and Signal Processing Branch. He is the autonomy lead on the Nano-satellite Technology Team. He has served as the lead electrical engineer for numerous flight projects at GSFC and at MIT Lincoln Laboratory, including the Cassini/ CAPS Spectrum Analyzer and the IMAGE/ LENA Command and Data Handling System. He received his B.S., M.S. and Electrical Engineer degrees from MIT.

Bob Beaman is a senior engineer in the GSFC Power Systems Branch. He is the lead for Power Systems on the Nano-satellite Technology Team. He has extensive experience with aerospace Electrical Power Systems, and is an expert in advanced and alternative power production, storage, and distribution techniques.

Dr. Joseph A. Mica is an expert in aerospace and military electrical and control systems in the GSFC Systems, Technology, And Advanced Concepts Directorate. He has over twenty years of experience and has lead or supported a variety of flight, electrical, and software projects including: Hubble Space Telescope, UARS, GPS, Space Station, and others. He received his B.S.E.E. from Washington University, where he also completed a Graduate Program in Artificial Intelligence.

Walter F. Truszkowski is an Artificial Intelligence leader working in the GSFC Applied Engineering and Technology Directorate. He has many years of experience with knowledge based engineering, particularly as applied to GSFC's research and development of ground-control systems capable of "lights out" operation. Agent technologies are a central focus of his research.

Dr. Michael L. Rilee is a Computational Scientist supporting the Solar-Terrestrial Probe Science Application Team of NASA's Remote Exploration and Experimentation project. He is currently researching on board, autonomous methods of spacecraft sensor data analysis and information extraction. His background is in Plasma Astrophysics. He received his B.A. from the Univ. of Virginia, Charlottesville and his M.S. and Ph.D. from Cornell University.

David E. Simm has a broad range of experience in the aerospace and electronics industries spanning more than 25 years. In addition to Spacecraft Flight Operations Engineering work, he has considerable experience in the application of Lithium Ion, Lithium Metallic, and Lithium Polymer batteries. Most recently he is working on the Nanosat Electrical Power System at NASA Goddard Space Flight Center. Mr. Simm is a graduate of the University of Maryland, College Park.